Asteroid Bennu Temperature Maps for OSIRIS-REx Spacecraft and Instrument Thermal Analyses

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A thermophysical model has been developed to generate asteroid Bennu surface temperature maps for OSIRIS-REx spacecraft and instrument thermal design and analyses at the Critical Design Review (CDR). Two-dimensional temperature maps for worst hot and worst cold cases are used in Thermal Desktop to assure adequate thermal design margins. To minimize the complexity of the Bennu geometry in Thermal Desktop, it is modeled as a sphere instead of the radar shape. The post-CDR updated thermal inertia and a modified approach show that the new surface temperature predictions are more benign. Therefore the CDR Bennu surface temperature predictions are conservative.

Nomenclature

A	=	bolometric albedo
a'	=	surface area of Bennu
da'	=	infinitesimal surface area of the integral
C	=	specific heat
δt	=	delta time
δT	=	delta temperature
ε	=	bolometric emissivity
F	=	view factor from a facet da at a point r to da′ at r′
J_{IR}	=	infrared radiosity (i.e., infrared flux emitted by the facet)
J_v	=	visible-light radiosity (i.e., visible light reflected by the facet)
Γ	=	thermal inertia
κ	=	thermal conductivity
l_s	=	penetration heat scale length
μ	=	directional cosine (i.e., scalar product of the normal to the facet and the direction to the Sun)
ϕ	=	longitude (on Bennu)
ρ	=	density
r	=	r is the positional vector of the facet r'viewed by the facet at r
r'	=	r is the positional vector of the facet r'viewed by the facet at r
s	=	heliocentric distance
σ	=	Stefan-Boltzmann constant
S_Θ	=	solar flux at heliocentric distance of 1 astronomical unit

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T	=	temperature
Θ	=	latitude (on Bennu)
z	=	coordinate depth in the subsurface (z=0 at the surface).

I. Introduction

THE NASA's Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission is to obtain a pristine sample of the carbonaceous asteroid (101955) Bennu. It is a planetary science mission in NASA's New Frontiers Program. It is scheduled for launch from Cape Canaveral in September 2016, encountering asteroid Bennu in October 2018. The mission includes a study with global mapping of the Bennu surface from a distance of 5 km to a distance of 0.7 km for up to 505 days. Its return to Earth is scheduled for September 2023 in a Stardust-heritage Sample Return Capsule (SRC). There are five instruments on the spacecraft. Asteroid Bennu has an approximately 0.5 km diameter, a 4.3-hour rotation period, and a 436.6-day orbit of Sun. Figure 1 shows an artist's impression of the surface of the Bennu wrapped on the radar shape.[1] Figure 2 shows the Bennu orbit.[1] Figure 3 is an artist's concept of the OSIRIS-REx spacecraft preparing to collect a sample from Bennu.[1]

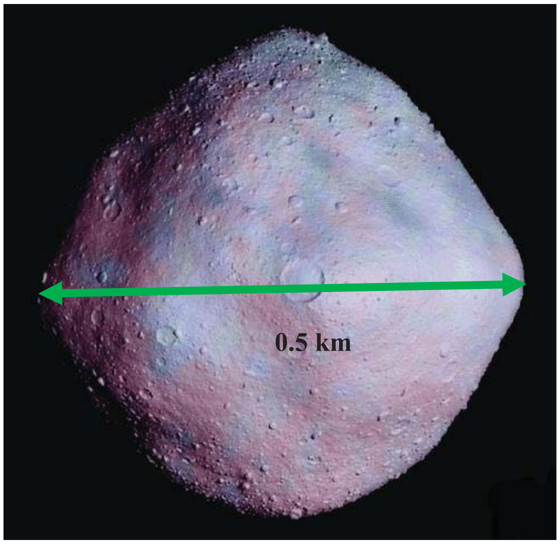


Figure 1. Asteroid Bennu (Image credit: NASA/GSFC/UA).

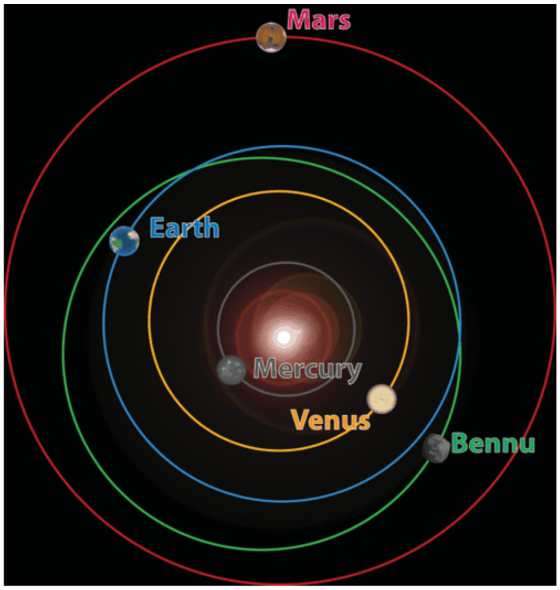


Figure 2. Asteroid Bennu Orbit (Image credit: NASA/GSFC/UA)

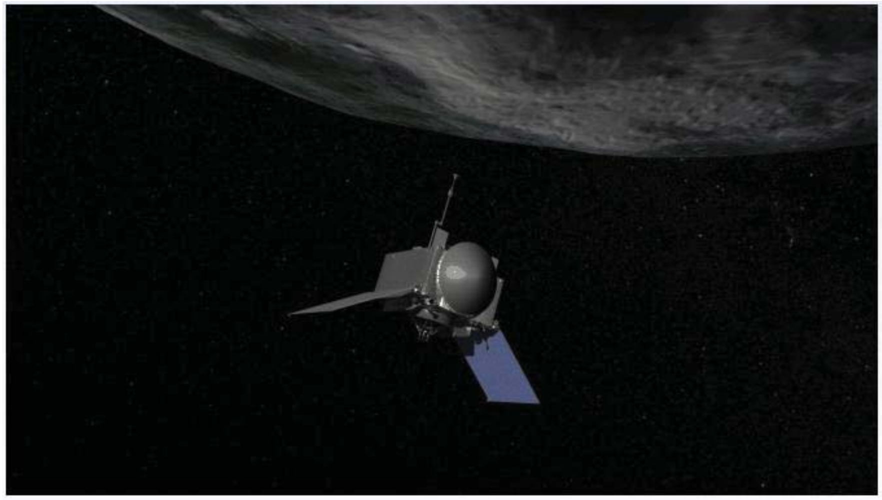


Figure 3. An Artist's Concept of OSIRIS-REx Spacecraft Preparing to Collect a Sample from Asteroid Bennu (Image Credit: NASA GSFC/Chris Meaney).

Asteroid Bennu is closer to the Sun than the majority of asteroids, which are at 2 to 3.5 astronomical units (AU). Bennu is at 0.897 to 1.387 AU and has a low albedo (0.045±0.015 with 3-sigma uncertainty) [2]. Its surface is expected to be quite warm near the equator, but relatively cool at higher latitudes. The OSIRIS-REx spacecraft and instrument thermal engineers must have an accurate picture of this thermal environment in order to do thermal design.

II. Objective

The objective of this paper is to present a methodology of developing the asteroid Bennu surface temperature maps for OSIRIS-REx spacecraft and instrument thermal design and analyses.

III. OSIRIS-REx Mission Phases Affected by Bennu Temperatures

After launch, the Outbound Cruise phase is 2 years and 1 month long. At the end of the Outbound Cruise, an Asteroid Approach Maneuver is planned for October 2018. An Asteroid Departure Maneuver is planned for March 2021. The mission phases between these two maneuvers are affected by the Bennu surface temperatures. They are described below.

A. Detailed Survey

The Detailed Survey phase is a long transient case at a 3.5 to 5-km altitude. Science observations are one rotation of Bennu (4.3 hours). There are seven equatorial stations at a 5-km altitude and four "baseball diamond" observations at a 3.5-km altitude (Figure 4). The altitudes are 7 to 10 times the diameter of Bennu. The Bennu surface temperature does not affect the temperatures of the spacecraft or instruments significantly.

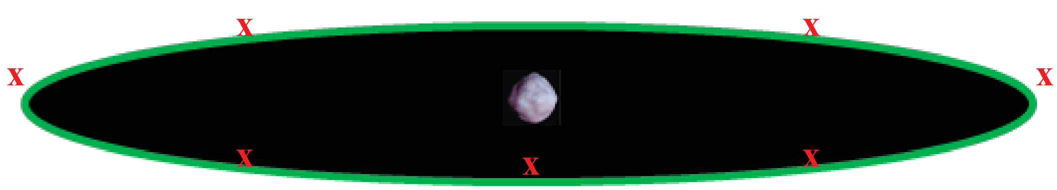


Figure 4. Detailed Survey.

B. Orbital Phase

Orbital A is a 1.5-km radius terminator orbit with a 1.25-km altitude. Orbital B is a 1-km radius terminator orbit with a 0.75-km altitude (Figure 5). The altitudes are 1.5 to 2.5 times the diameter of Bennu. The heliocentric

distance is 0.897 to 1.387 AU. For spacecraft and instrument thermal analyses, the Bennu surface temperatures are included in the worst hot case for hot biasing the spacecraft and instruments, and neglected in the worst cold case for cold biasing.

Figure 5. A 1-km Terminator Orbit -- View from Sun.

C. Reconnaissance

Reconnaissance overflights start from a 750-m altitude terminator orbit. Four 225-m altitude overflights and two 525-m altitude overflights are planned (Figure 6). For both overflights, approach is -Z sun-point, -X away from Bennu and slew to nadir-point for 30 minute observations. There is a total of 45 minutes in nadir-point with instruments powered on for 35 minutes. The heliocentric distance is 0.897 AU. For spacecraft and instrument thermal design and analyses, the Bennu surface temperatures are included in the worst hot case for hot biasing the spacecraft and instruments.

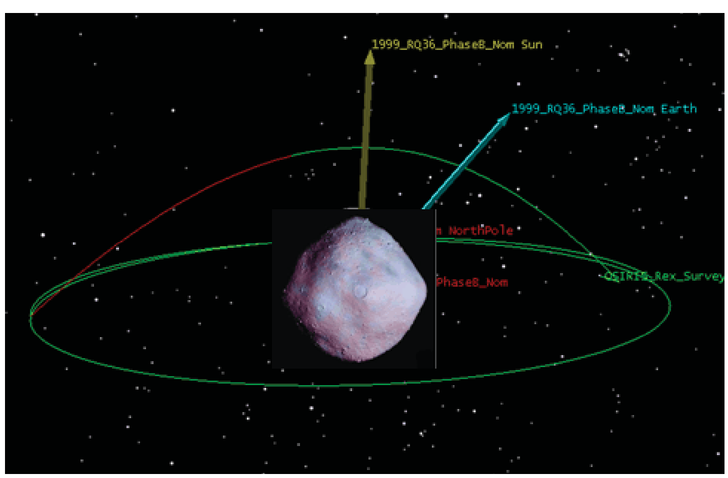


Figure 6 . 525 m Overflight.

D. Touch-and-Go

Touch-and-Go (TAG) is in a 750-m altitude terminator orbit and appropriate instruments are preheated. It is split into two steps (Figure 7): Departure Burn to Checkpoint Maneuver at 125-m altitude; Checkpoint Maneuver through Sample Acquisition and Back-away Maneuver. Equatorial overflight is the bounding hot case. The LIDAR, TAGCAMS, SamCam, MapCam, OTES and OVIRS are powered on. From Matchpoint to TAG, the Bennu surface temperature is fixed at 350K (77˚C) per OSIRIS-REx Environment Requirement Document. The heliocentric distance is 0.897 to 1.387 AU. The TAG site is nominally 65˚ from the Sun on the afternoon side. For spacecraft and instrument thermal design and analyses, the Bennu surface temperatures are included in both the worst cold case and worst hot case.

Figure 7 . TAG.

IV. Methodology of Generating Bennu Surface Temperature Maps

The methodology of generating Bennu surface temperature maps is described in details below. Also the worst hot case and worst cold case surface temperature maps are presented. The effect of the Bennu regolith thermal inertia on the surface temperature predictions is discussed.

A. Bennu Temperature Format for Spacecraft and Instrument Thermal Engineers

The OSIRIS-REx spacecraft and instrument thermal engineers use Thermal Desktop software for thermal design and analysis. It cannot easily incorporate three-dimensional lookup tables required for full directional correction. Therefore two-dimensional temperature maps for worst hot and cold cases are used to assure adequate thermal design margins. To minimize the complexity of the Bennu geometry in Thermal Desktop, it is modeled as a sphere instead of the radar shape.

B. Model for Predicting Bennu Surface Temperatures

To meet the need for Bennu surface temperatures for spacecraft and instrument thermal analyses, a thermophysical model (TPM) was developed by Emery and Delbo[3]. The TPM is constrained by the most up-to-date data available of thermal flux from Bennu. For instance, the initial model was constrained by the Spitzer and Herschel telescopic observations of Bennu. The model inputs and outputs increase in detail as the mission progresses, and the model development follows a similar trajectory. For spacecraft and instrument thermal analyses, a Preliminary TPM was used for Preliminary Design Review (PDR) and an Intermediate TPM was used for Critical Design Review (CDR). The Final TPM will be used only during operations at Bennu. The Intermediate TPM includes corrections for directional effects of surface roughness. A facet consists of sub-elements that are tilted in different directions. They account for directional effects of surface roughness. Also one standard deviation is included.

From the OSIRIS-REx ERD, a thermal inertia of 50 J m^{-2} $s^{-0.5}$ K^{-1} is used only at altitudes below Matchpoint (about 50 m). For the rest of the overflight cases, a thermal inertia of 400 J m^{-2} $s^{-0.5}$ K^{-1} is used. A heliocentric distance, s, of 1 AU is used. Thermal engineers scale the temperatures (T) for other heliocentric distances by using the relationship $T\sqrt{s}$=constant.

The Intermediate TPM includes temperature differences between a rough surface and smooth surface for a grid of viewing geometries (emission angle from 0˚ to 80˚ in 10˚ steps, and azimuth angle from 0˚ to 360˚ in 10˚ steps). It also shows color images of effective temperatures for different viewing geometries. From these results, corrections for directional effects of surface roughness were accounted for in spacecraft and instrument thermal analyses.

Temperatures for a smooth surface on the radar shape were calculated first, and projected onto a sphere for use in Thermal Desktop software for spacecraft and instrument thermal analysis.

The Intermediate TPM[3] calculates a) the asteroid temperature distribution at the surface and in the subsurface, b) emitted infrared flux as a function of physical parameters such as size, microscopic shape, thermal inertia, albedo, surface roughness and spin vector, and orbital parameters, such as heliocentric position (and its history). The view factor from a facet da at a point r to da′ at r′ is defined as the fraction of the radiative energy leaving the former and directly striking the latter. The thermal conductivity in the subsurface includes the following. A bolometric emissivity of 0.9 is used for Bennu.

Surface boundary condition:

$$\epsilon\sigma T^4(r,z,t) - \kappa\frac{\partial T(r,z,t)}{\partial z} = (1-A)S_\odot r^{-2}(t)\mu(\theta,\phi,t) + \int_\Sigma \left(J_V(r') + \frac{\epsilon}{\alpha}J_{IR}(r')\right)F(r,r')da' \quad (1)$$

Heat diffusion in regolith:

$$\rho C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\kappa\frac{\partial T}{\partial z} \simeq \kappa\frac{\partial T^2}{\partial^2 z} \quad (2)$$

Boundary condition at regolith depth:

$$\left(\frac{\partial T}{\partial z}\right)_{z>>l_s} = 0 \quad (3)$$

Thermal inertia provides information about the presence (or absence), depth and thickness of regolith, and the presence of exposed rocks on the surface of atmosphereless bodies. Figure 8 shows regolith for various thermal inertia.[5]

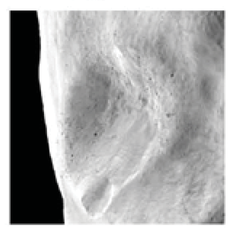
25143 Itokawa	433 Eros	The moon	21 Lutetia
$\Gamma = 750$	$\Gamma = 150$	$\Gamma = 40 - 50$	$\Gamma = 20$
			
Coarse regolith and boulders	Finer and thicker regolith	Mature and fine regolith	Very fine regolith

Figure 8. Regolith for Various Thermal Inertia.

Bennu temperature maps were generated in July 2013 for spacecraft and instrument thermal analyses. Thermal inertia of 50 J m^{-2} $s^{-0.5}$ K^{-1} and 400 J m^{-2} $s^{-0.5}$ K^{-1} were used for each of the hot, cold and nominal cases. For spacecraft and instrument thermal analyses in for Critical Design Review (CDR), a conservative approach was used. The Bennu surface temperatures for the above cases are:

● Smooth surface effective temperature plus weighted average of delta-Ts (differences between a rough surface and smooth surface) greater than zero for worst hot case..

● Smooth surface effective temperature plus weighted average of delta-Ts smaller than zero for worst cold case.

● Smooth surface effective temperature plus weighted average of all delta-Ts (positive and negative) for nominal case.

Weighting factor is a function of view factor or form factor from the spacecraft to a facet.

C. Bennu Surface Temperature Maps for CDR

Figures 9 and 10 present the Bennu surface temperature predictions for the worst hot case with thermal inertia of 400 and 50 J m^{-2} $s^{-0.5}$ K^{-1} respectively for CDR spacecraft and instrument thermal analyses. Figure 11 shows the Bennu surface temperature map in the thermal model in Thermal Desktop for the worst hot case with thermal inertia of 400 J m^{-2} $s^{-0.5}$ K^{-1}. Figures 12 and 13 present the Bennu surface temperature predictions for the worst cold case with thermal inertia of 400 and 50 J m^{-2} $s^{-0.5}$ K^{-1} respectively.

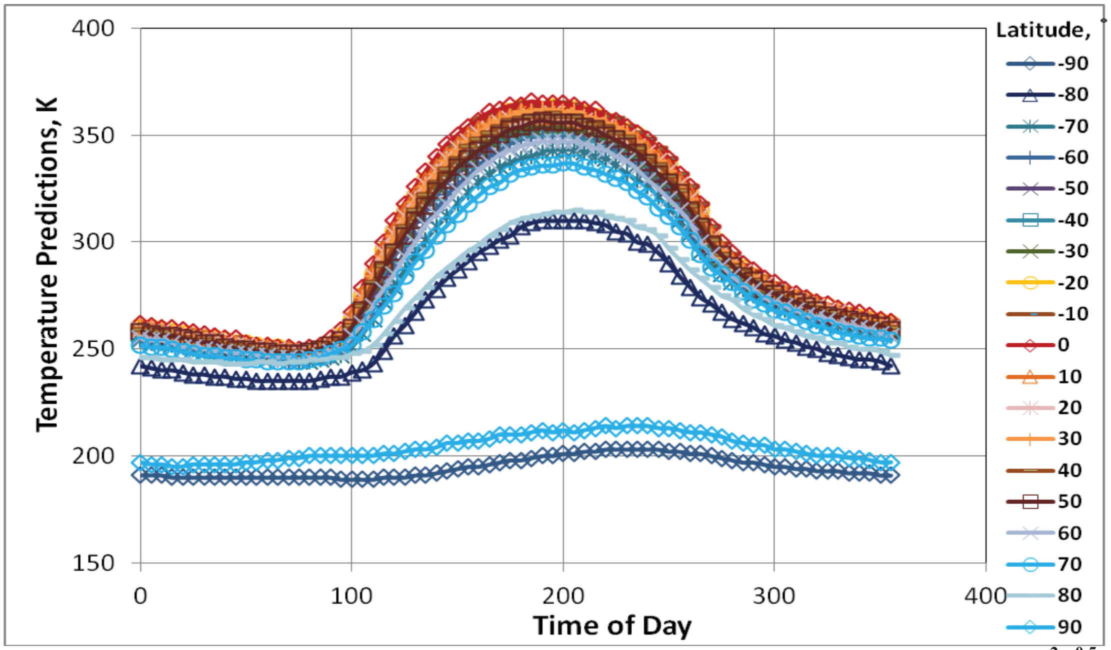


Figure 9. Bennu Temperature Predictions for Worst Hot Case with Thermal Inertia of 400 $Jm^{-2}s^{-0.5}K^{-1}$.

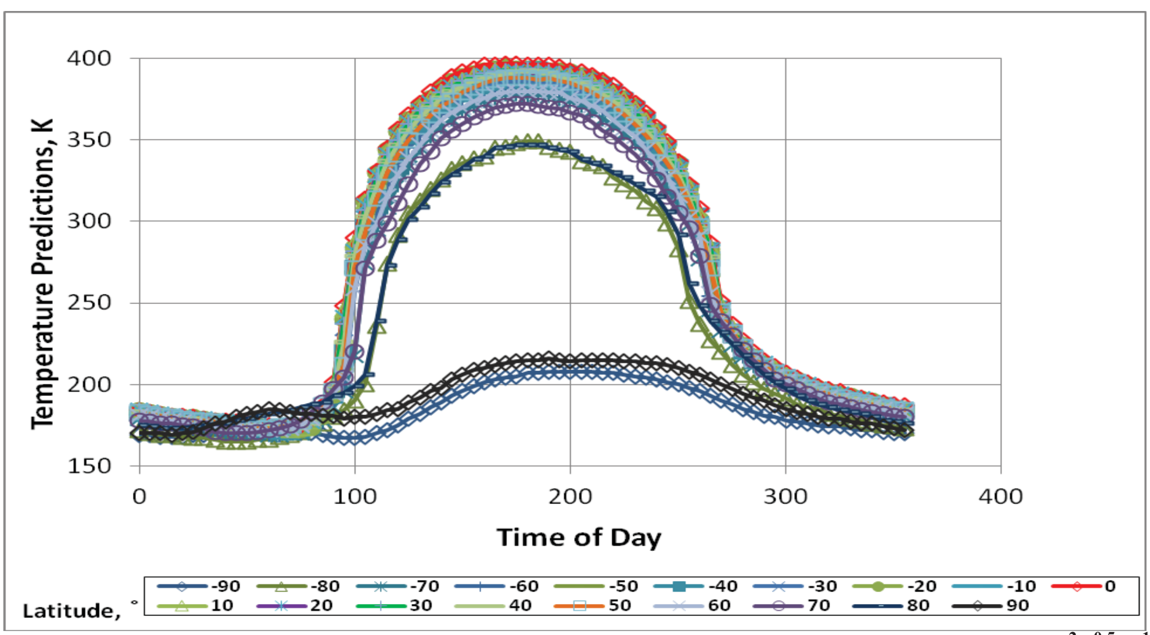


Figure 10. Bennu Temperature Predictions for Worst Hot Case with Thermal Inertia of 50 $Jm^{-2}s^{-0.5}K^{-1}$.

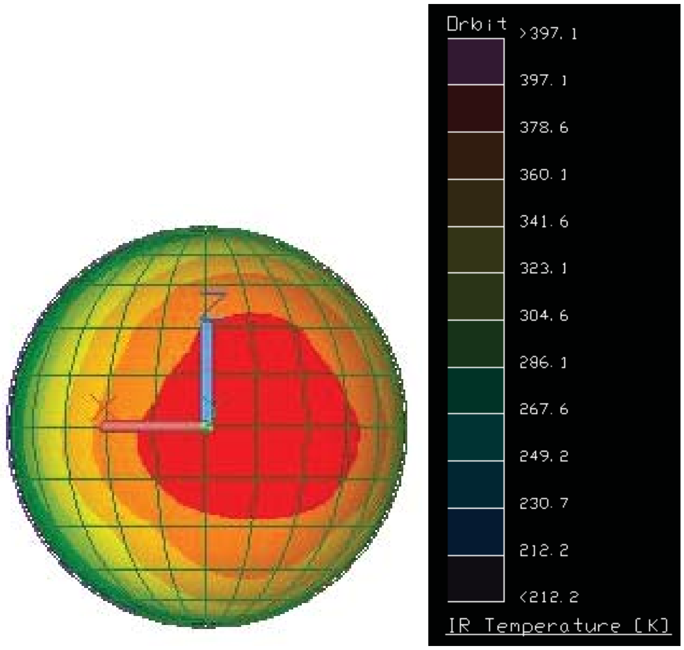


Figure 11. Bennu Temperature Map for Worst Hot Case with Thermal Inertia of 400 Jm^{-2}s$^{-0.5}$K^{-1}.

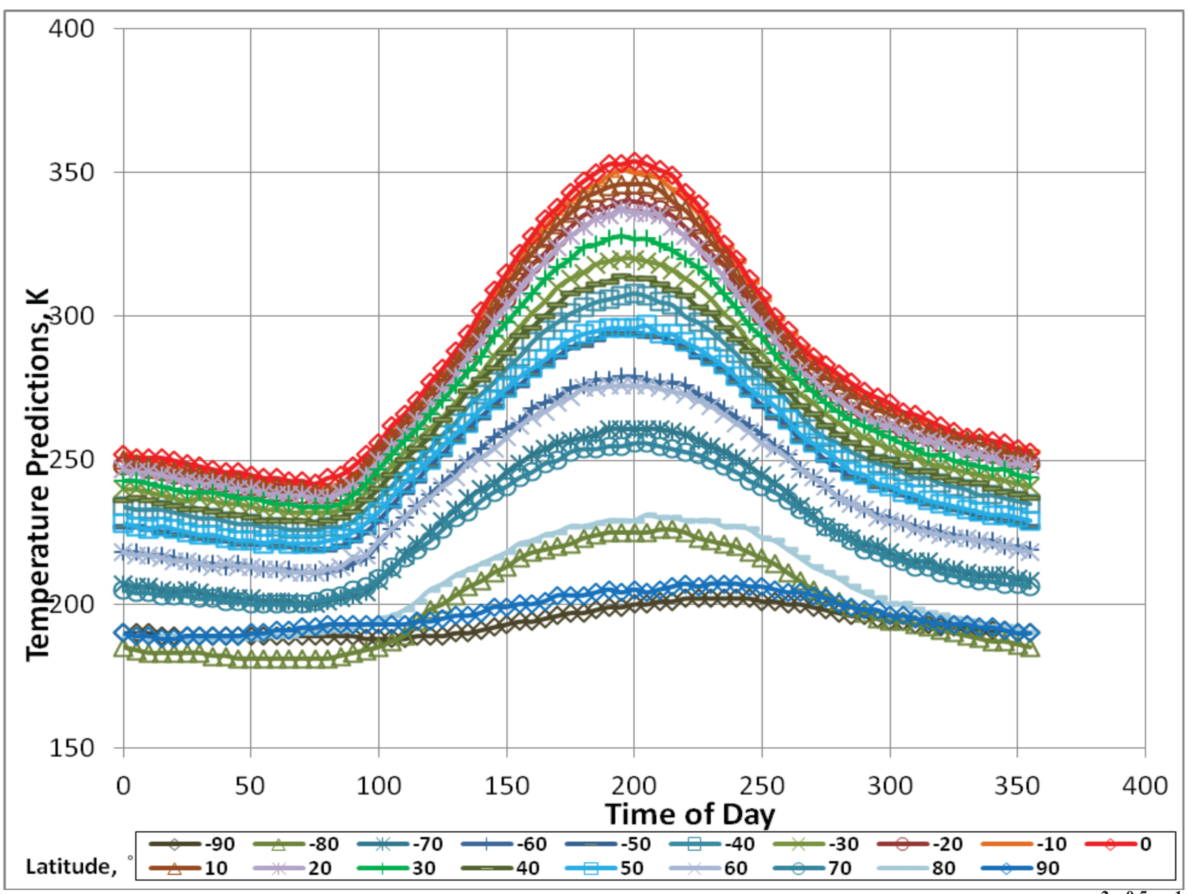


Figure 12. Bennu Temperature Predictions for Worst Cold Case with Thermal Inertia of 400 Jm^{-2}s$^{-0.5}$K^{-1}.

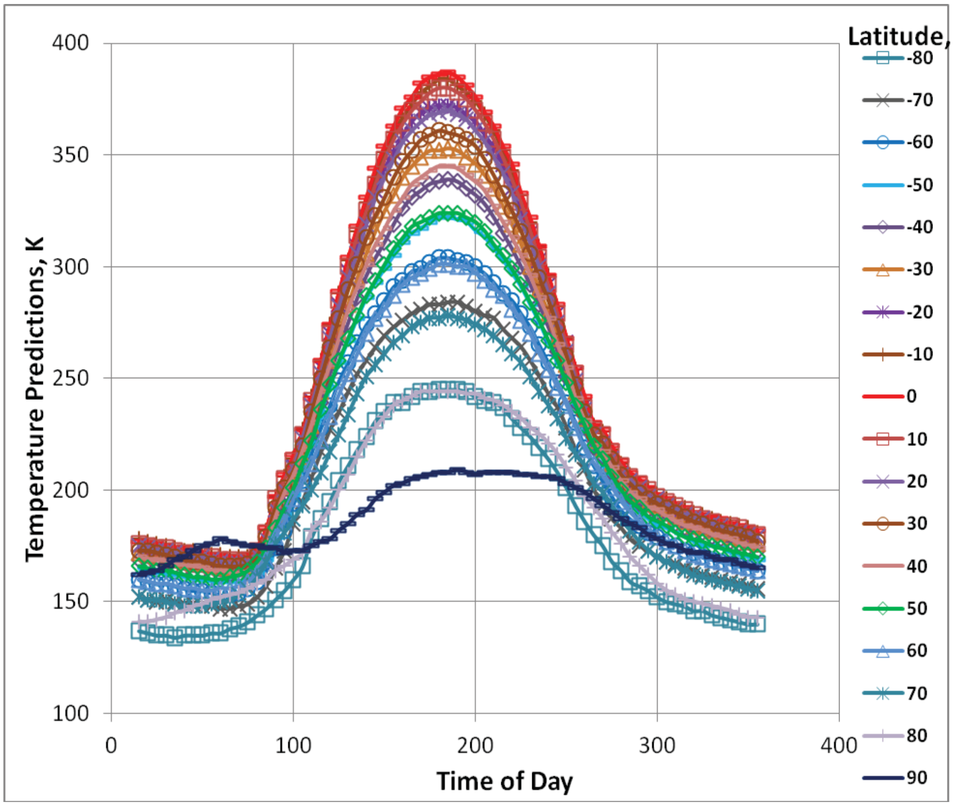


Figure 13. Bennu Temperature Predictions for Worst Cold Case with Thermal Inertia of 50 $Jm^{-2}s^{-0.5}K^{-1}$.

D. Updated Bennu Thermal Inertia

Recently a detailed analysis of the Spitzer data in terms of thermal properties was completed by Emery et al.[4] It revealed that the updated Bennu thermal inertia is 310±70 J m^{-2} $s^{-0.5}$ K^{-1} [+/-180 3-sigma]. Using this new thermal inertia range, a modified approach is used to prevent Bennu surface temperature predictions from over-conservative.

- For worst hot case, use thermal inertia of 240 J m^{-2} $s^{-0.5}$ K^{-1} and smooth surface effective temperature plus weighted average of all delta-Ts (i.e., differences between a rough surface and smooth surface) (positive and negative; was positive only).

- For nominal case, use thermal inertia of 310 J m^{-2} $s^{-0.5}$ K^{-1} and smooth surface effective temperature plus weighted average of all delta-Ts (positive and negative; was positive and negative).

- For worst cold case, use thermal inertia of 380 J m^{-2} $s^{-0.5}$ K^{-1} and smooth surface effective temperature plus weighted average of all delta-Ts (positive and negative; was negative only).

The new Bennu surface temperatures are more benign than those used for spacecraft and instrument thermal design and analyses for CDR in both the worst hot case and worst cold case. Figures 14 and 15 present the delta temperature predictions, which are differences between the CDR predictions and the new predictions, for the hot case and cold case respectively. The new Bennu surface temperatures add margins to the CDR thermal design. Unless some relief in thermal design margin is needed at the CDR (instrument or spacecraft), there is no need to revise the thermal design and analysis after the CDR, even if the Bennu thermal inertia and surface temperatures are updated in the ERD.

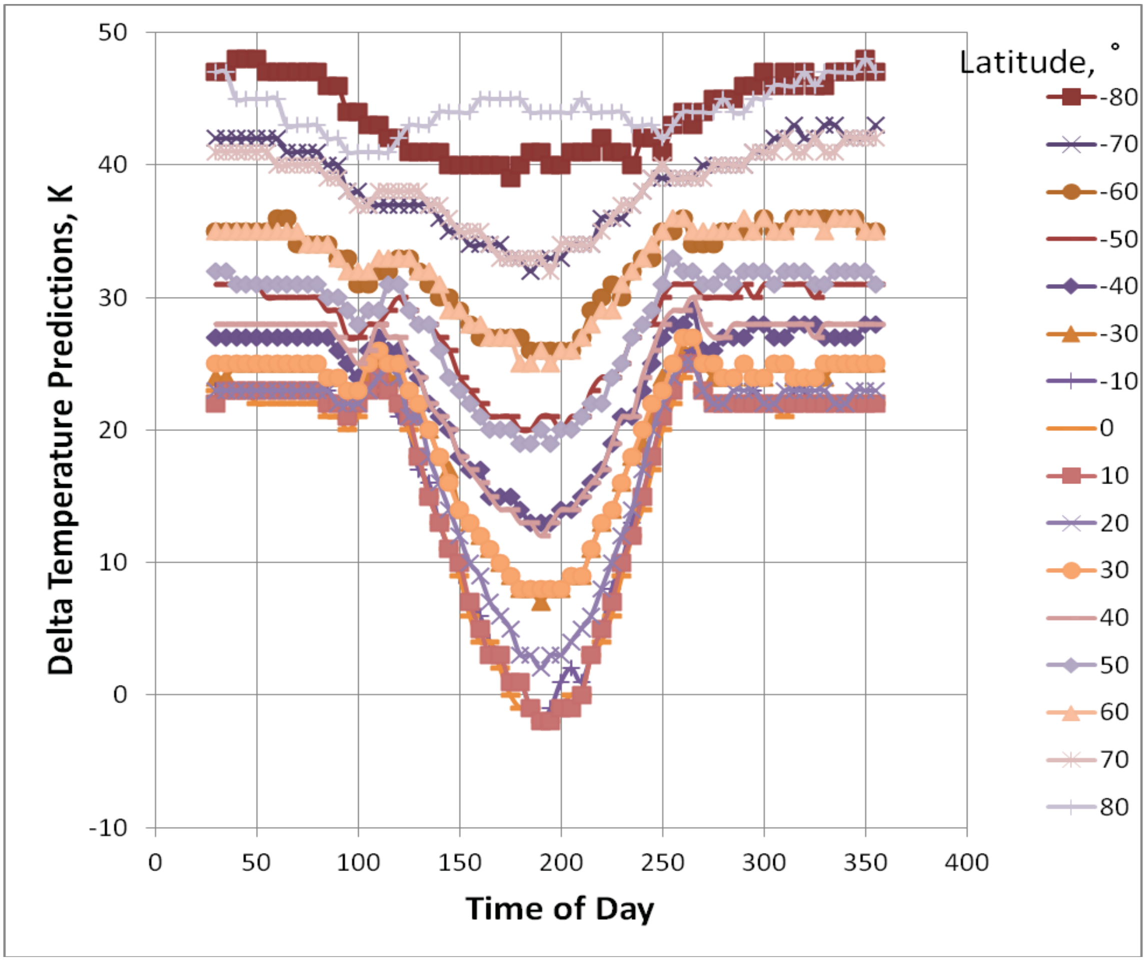


Figure 14. Difference between CDR Predictions and New Predictions in Worst Hot Case.

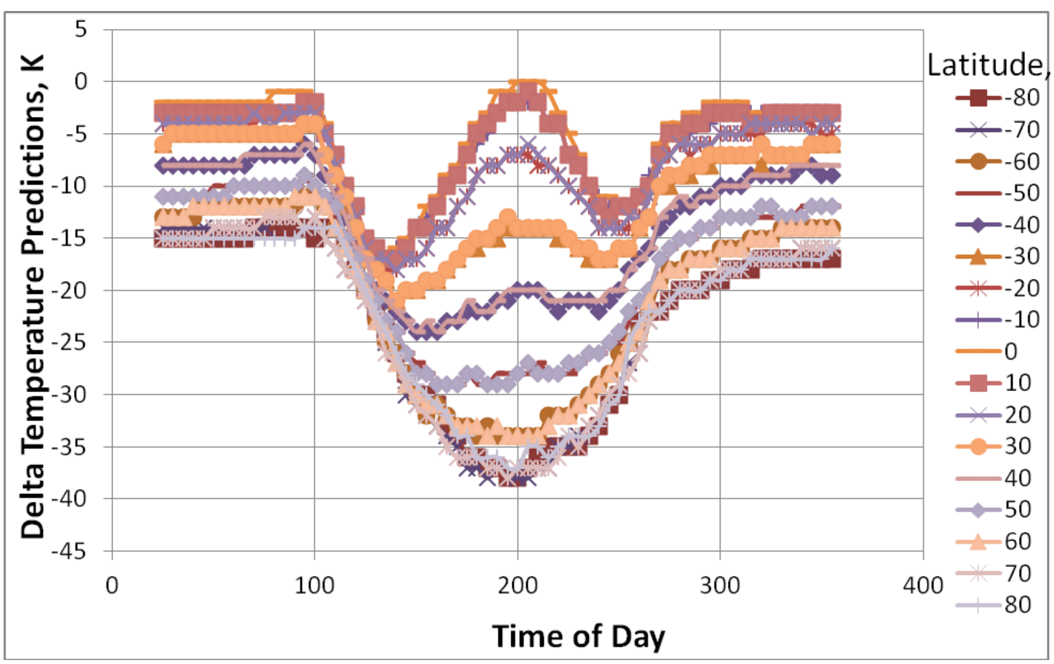


Figure 15. Difference between CDR Predictions and New Predictions in Worst Cold Case.

V. Conclusion

The new Bennu surface temperatures are more benign than those used for CDR spacecraft and instrument thermal design and analyses in both the worst hot case and worst cold case. The new Bennu surface temperatures add margins to the CDR thermal design. Unless some relief in thermal design margin is needed at the CDR (instrument or spacecraft), there is no need to revise the thermal design and analyses.

References

[1]http://www.osiris-rex.lpl.arizona.edu/?q=gallery

[2]Hergenrother, C. W., et al., "Lightcurve, Phase and Color Photometry of the OSIRIS-REx Target Asteroid (101955) Bennu", Incarus Icarus 226, 663–670, Sept. 2013.

[3]Emery, J. P., et al., "How Cool is Bennu? Thermal Model for CDR and Beyond", poster presented at OSIRIS-REx Science Team Meeting, Houston, TX, July 2013.

[4]Emery, J. P. et al., "Thermal Infrared Observations and Thermophysical Characterization of OSIRIS-REx Target Asteroid (101955) Bennu", Incarus 234, 17–35, May 2014.